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INFLUENCE OF WATER, SQUALANE, AND METHANOL ON THE
MECHANICAL STRENGTH OF A BEARING-TYPE STEEL

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

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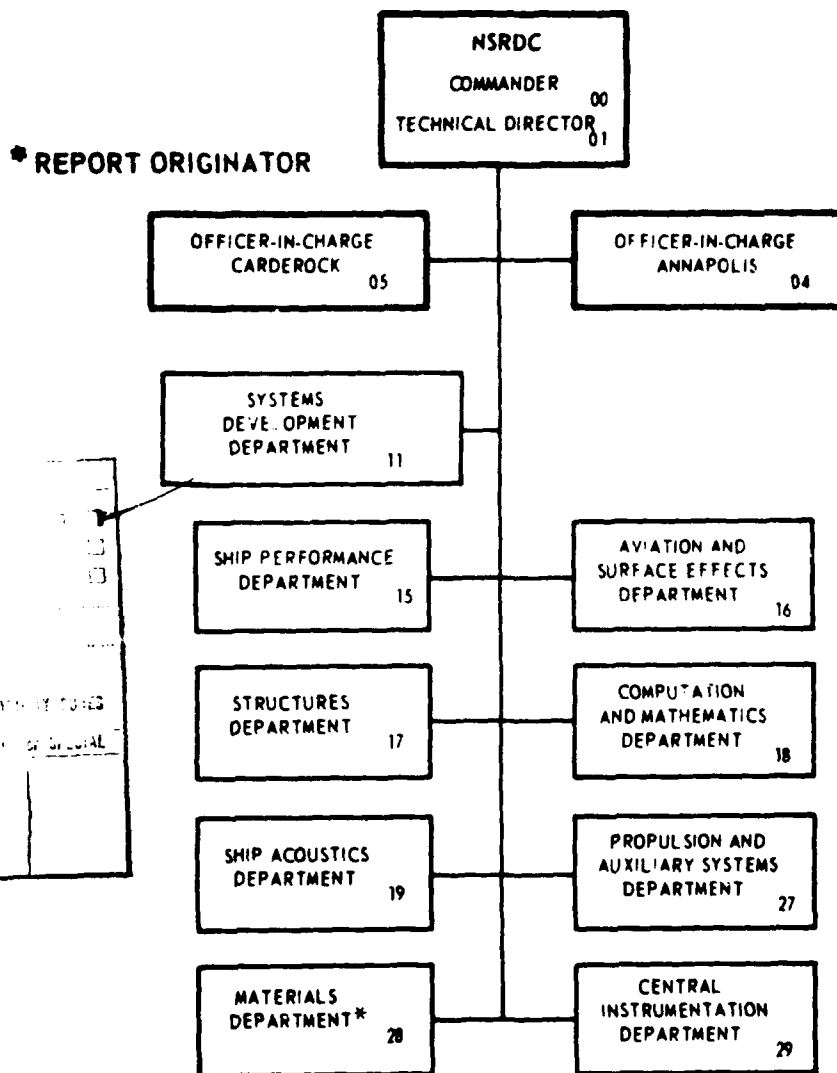
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ADMINISTRATIVE INFORMATION

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INTRODUCTION

There continues to be considerable interest from a practical as well as an academic point of view in the detrimental influence of water on bearing-type steels. Ultimately, this interest is related to the reliability of machinery, particularly when operating in a marine environment. In a recent investigation it was shown that a water content of 0.01%, dissolved in a liquid hydrocarbon, can significantly decrease the rolling contact fatigue life of AISI 52100 bearing steel being lubricated by the hydrocarbon.¹ This was in agreement with an extended earlier work on this subject.^{2,3} It has further been demonstrated that water vapor accelerates subcritical crack growth in a high-strength steel and that the crack propagation rate becomes constant and equal to that occurring in liquid water at a limiting relative humidity.⁴ Another study which was concerned with the embrittlement of steels by various organic liquids concluded that the observed embrittlement was due to the water dissolved in these liquids.⁵

As a result of an investigation on the influence of water in a hydrocarbon lubricant (squalane) on rolling-contact fatigue,¹ it was decided to further investigate the mechanism by which water reduces the mechanical strength of steel by using thin sheet specimens in uniaxial tensile stress.

EXPERIMENTAL

APPARATUS

Experiments were conducted with a table model Instron[®] machine utilizing cross-head speeds ranging from 0.01 to 0.00005 cm/min.* A photograph of the machine is shown in figure 1. A small inner chamber to keep the environment (liquid, gas, or both) in contact with the specimen gage length has been previously described.⁶ An outer chamber served as an oven and maintained inner chamber temperature at $50^{\circ} \pm 0.02^{\circ}\text{C}$. Figure 2 is a photograph of the apparatus. For those experiments in which extensometry was employed, a device was constructed which transmitted the mechanical motion of strain from the inner chamber to the cool zone outside the outer chamber. A photograph of the assembly prior to mounting in the Instron machine is shown in figure 3. This figure also provides a close-up view of the inner chamber.

SPECIMEN PREPARATION AND MATERIALS

Specimens were made from a thin steel section similar in composition and hardness to bearing ball steel as shown in table 1.

A conventional dumbbell configuration was used with a gage length of 2 cm and a thickness and width of 0.01 and 0.36 cm, respectively. Specimens were gang-formed by grinding and electrodischarge-machining to minimize cold-working and machining marks. They were then wet (cetane) polished to near-optical finish with 0.3 micrometer particle size aluminum oxide powder and stored in a desiccator over magnesium perchlorate.

¹ Superscripts refer to similarly numbered entries in the Technical References at the end of the text.

* Abbreviations used in this text are from the *ASA Style Manual*, 1973, unless otherwise noted.

TABLE I
CHEMICAL COMPOSITION AND
HARDNESS OF BEARING STEELS

	% of Weight	
	Tensile Test Steel	AISI 52100 Bearing Ball Steel
C	1.04	1.02
Si	0.25	0.31
Mn	0.35	0.33
S	0.010	0.009
P	0.019	0.017
Ni	0.04	0.11
Cr	0.21	1.55
Mo	0.008	0.006
Hardness Rockwell C	66	63

PROCEDURE

Accidental prestrain of the steel tensile specimen was avoided by use of a grip support which remained in place until the specimen was completely mounted in the Instron TM test machine. This grip support is shown in figure 3.

For maintaining a dry environment, either oxygen or argon was passed through a calcium sulfate drying column prior to entering the chamber. For maintaining moist environments, the gas was bubbled through a tower containing deionized water before entering the outer chamber and then through a second tower, which was at temperature inside the outer chamber, before entering the inner chamber and bubbling through the fluid.

In all experiments, load was measured by a load cell whose output was calibrated and automatically plotted. In earlier experiments, strain measurement was by a deductive method in which the averaged cross-head movement of 12 calibration specimens, extended at different strain rates, was subtracted from the cross-head movement of each regular specimen. The remainder was the strain of the gage length since the calibration specimens were identical to the regular specimens, except that they contained no gage length. Subsequent experiments employed extensometry for strain measurement.

Experiments were conducted at several cross-head speeds and in a number of different environments: dry and humidified argon gas; deionized water; synthetic sea water (ASTM Method D665); a dry hydrocarbon lubricant, hexamethyl tetracosane (squalane) purified by successive percolation through finely divided silica gel; squalane containing dissolved water; and reagent grade methanol. Methanol was used to assess its chemical reactivity to stressed steel relative to water.

RESULTS

Numerous experiments at different cross-head speeds and under different environments demonstrated that the elastic and plastic properties of the steel specimens remained the same but that specimens failed at different points on the stress/strain curve depending on the environment. The data of interest for each experimental condition were the stress and strain at fracture. Figure 4 shows these data obtained by the deductive method of strain measurement plotted with the average stress/strain curve for this steel. Each data point represents the stress and strain attained by the specimen at the moment of fracture and is therefore the end-point of the stress/strain curve for that specimen. Figure 5 shows results obtained using the extensometric method for measuring strain. This demonstrates that the two methods are in agreement with less scatter being shown by the latter procedure. Consequently, it was decided to combine the data for further analysis.

The fracture strain for each experiment was determined from the combined data. By considering the results for a dry argon environment, as a standard of comparison, the percent reduction in fracture strain due to each aggressive environment was calculated at several strain rates. This is shown in table 2. The results in this table, along with those in figures 4 and 5, permit the drawing of several conclusions.

TABLE 2
PERCENT REDUCTION IN FRACTURE STRAIN DUE TO INFLUENCE
OF ENVIRONMENT USING DRY ARGON AS COMPARISON

	Cross-Head Rate, cm/min								Avg No. of Specimens for Each Result
	0.01	0.005	0.001	0.0005	0.0003	0.0002	0.0001	0.00005	
Approximate Time of Exposure to Environment, min	7	14	70	140	250	400	700	1500	
<u>Environment</u>									
H ₂ O Purged with Humidified Argon	19		35	39			37	66	5
H ₂ O, Purged with Humidified Oxygen	20		37	28			22		4
Humidified Argon	17	8	27	20	52	22	19	21	1
200-300 p/m H ₂ O Dissolved in Squalane, Humidified Argon Purge	19	11	24	26	35	36	23	29	2
Dry Squalane, Dry Argon Purge, <5 p/m H ₂ O	3	8	6	8	19	11	15	10	2
Methanol, No Gas Purge	4	0	39	51		49	67	69	2
Avg = average									

CONCLUSIONS

- The presence of water in the environment, either free or dissolved in a hydrocarbon liquid, or as a gas, significantly reduces the fracture strain of the steel. All specimens exposed to water or methanol broke below the 0.2% offset yield point of the steel.
- There exists a trend toward greater embrittlement at lower strain rates with some specimens breaking below the proportional limit.
- The presence of dissolved oxygen in water appears to reduce the fracture strain at lower strain rates.
- Dry hydrocarbon liquid (squalane) causes a lesser but still measureable reduction in fracture strain.
- Methanol appears to be as aggressive an environment as liquid water.

DISCUSSION

The results of these experiments are in general agreement with those of Johnson and Willner⁴ who studied the influence of moisture on premature fracture of precracked specimens of a high-strength steel, H-11, with a yield strength of 230 thousand pounds per square inch (ksi). They concluded that water can exert a controlling influence upon the fracture behavior of high-strength steel. The high-strength steel (yield strength 280 ksi) used in the experiments described in this paper exhibited high susceptibility to water in the environment without the presence of an artificial crack-like flaw, some specimens breaking below the proportional limit. All specimens exposed to water or methanol broke below the 0.2% offset yield point. The influence of water on this steel varied directly with time of exposure to the environment at lower cross-head speeds. No influence of cross-head speed under dry argon conditions was observed, as seen in figures 4 and 5. Thus, for this steel, the relatively short time tests are influenced by the presence of water while longer time tests are dominated by it. This was pointed out by Johnson and Willner⁴ regarding the high-strength steel used in their experiments.

Dissolved oxygen appears to inhibit somewhat the deleterious influence of water at lower cross-head speeds as shown in table 2. Hancock and Johnson,⁷ using precracked H-11 steel, found the inhibiting effect of oxygen confined only to gas environments. In their work, oxygen dissolved in water did not influence crack-growth rate. However, their exposure times to oxygenated water were limited to less than 10 minutes, while the effect of oxygen shown in table 2 was not noticed until exposure times exceeded 100 minutes. Furthermore, Hanna, Troiano, and Steigerwald,⁸ using precracked 300M steel specimens (tensile strength 200 ksi) have shown that dissolved oxygen inhibits the influence of water on brittle fracture. The pronounced inhibiting influence of oxygen in gaseous environments was clearly shown by Hancock and Johnson⁷ and, as they pointed out, requires its adsorption on the steel surface in preference to water vapor. This effect is less noticeable for oxygen dissolved in liquid water, probably due to its relatively low concentration and the liquid diffusion barrier, making its influence time-dependent.

The influence of humidified argon (95% relative humidity) on reduction in fracture strain did not increase at longer exposure times, as was the case for liquid water. This was contrary to the results of Johnson and Willner⁴ who found that the influence of moisture above 60% relative humidity

on crack-growth rate was the same as liquid water. This was attributed to capillary condensation of water vapor into the artificial cracks of their specimens so that the crack interior was filled with water. The thin sheet tensile-specimens did not contain artificial cracks. Moreover, since the inhibiting influence of oxygen is so pronounced in the gaseous environment, the trace of oxygen present in the humidified argon may have sufficed to suppress somewhat the water vapor's embrittling influence at the longer exposure times.

The role of dissolved water in the squalane hydrocarbon lubricant on the embrittlement of high-strength steel is clearly shown in table 2. An increasing effect is seen at lower strain rates but not as pronounced as for liquid water. This may be due to increasing dependence on diffusion at the longer exposure times despite some agitation of the liquid by humidified argon purging. In general, the results agree with recent findings¹ which show a marked influence of dissolved water (100 p/m) in a hydrocarbon lubricant (squalane) on the rolling-contact fatigue life of AISI 52100 steel bearing balls. The lesser, but still noticeable effect of the dry hydrocarbon shown in table 2 agrees with the results of Swets and Frank⁹ who demonstrated that hydrogen from a hydrocarbon lubricant is absorbed by steel ball bearings. The molecular structure of the hydrocarbon may play a role in the availability of hydrogen from that source. Thus, the hydrocarbon used in these experiments, hexamethyl tetracosane, (squalane) contains six hydrogen atoms (known as tertiary hydrogens) which are more easily removed from the molecule than its other hydrogen atoms. A recent investigation¹⁰ examined the stress-corrosion cracking of AISI 52100 bearing steel in several different lubricants. It was found that the least embrittlement occurred with super refined petroleum-type lubricants while the most embrittlement occurred with diester-type lubricants. No attempt was made to relate the findings to the lubricants' water contents. It is suggested, however, that the molecular structure of the oils and their capacity for dissolving water played a role in the steel's embrittlement with the more significant role due to dissolved water.

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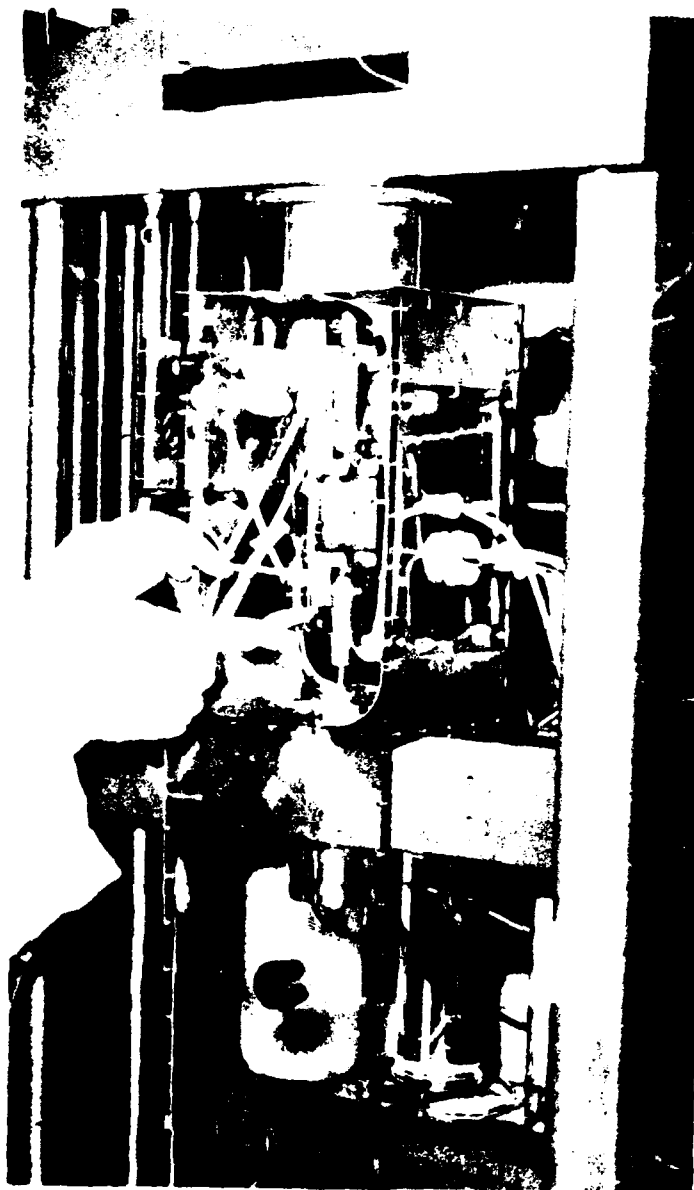


Figure 1
Tensile Machine

- | | |
|--------------------------------|------------------------------------|
| 1. Termination Actuator | 9. Second Bubble Tower |
| 2. Extensometer | 10. Check Valve |
| 3. Upper Pull Rod to Load Cell | 11. Lower Grip |
| 4. Strain Projector Rods | 12. Cross Head |
| 5. Outer Chamber | 13. Inner Chamber |
| 6. Heating Element | 14. Temperature Sensor |
| 7. Air Circulating Fan | 15. Gas Supply Tubes (Wet and Dry) |
| 8. Upper Grip | |

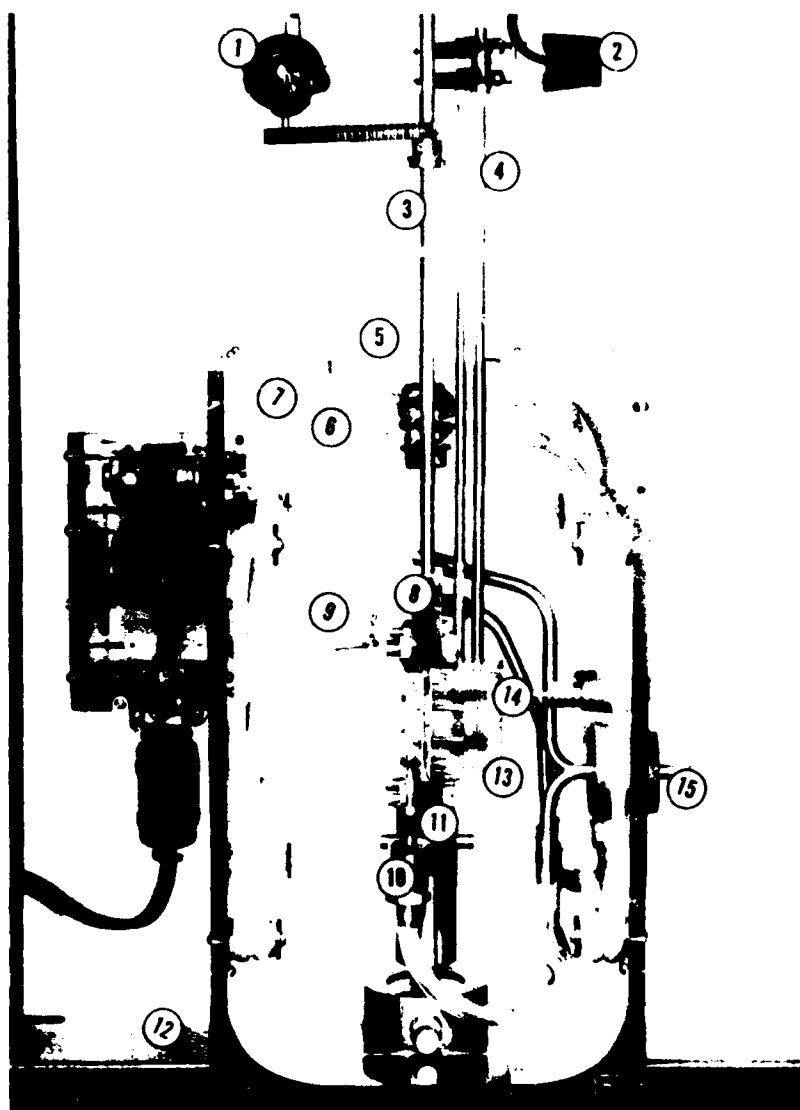


Figure 2
Environmental Tensile Assembly

- | | |
|------------------------------------|--------------------------------------|
| 1. Upper Pull Rod | 7. Inner Chamber Cover |
| 2. Extensometer Attachment Collars | 8. Inner Chamber Body |
| 3. Actuator Support | 9. Laminated Gasket |
| 4. Guide | 10. Lower Grip |
| 5. Strain Projector Rods | 11. Specimen Gage Length |
| 6. Upper Grip | 12. Knife-edge Follow-up Springs |
| | 13. Grip Positioner/Support Assembly |

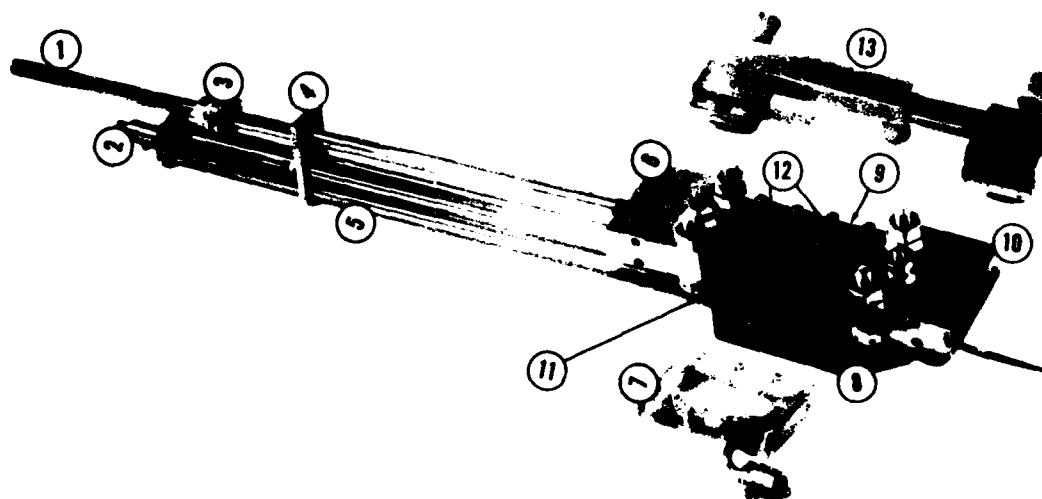


Figure 3
Extensometry Assembly and Inner Chamber

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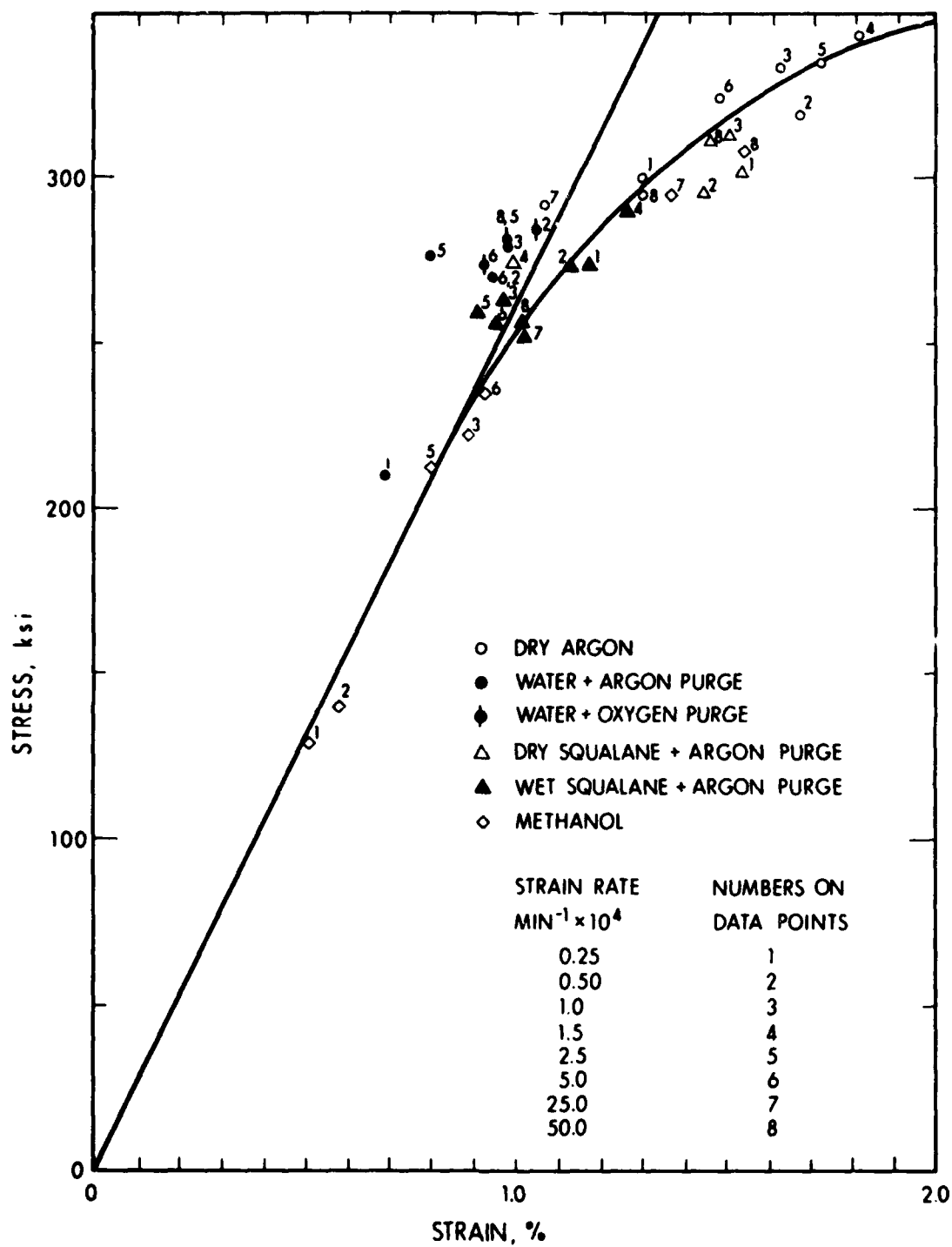


Figure 4
Stress and Strain at Fracture
Deductive Method

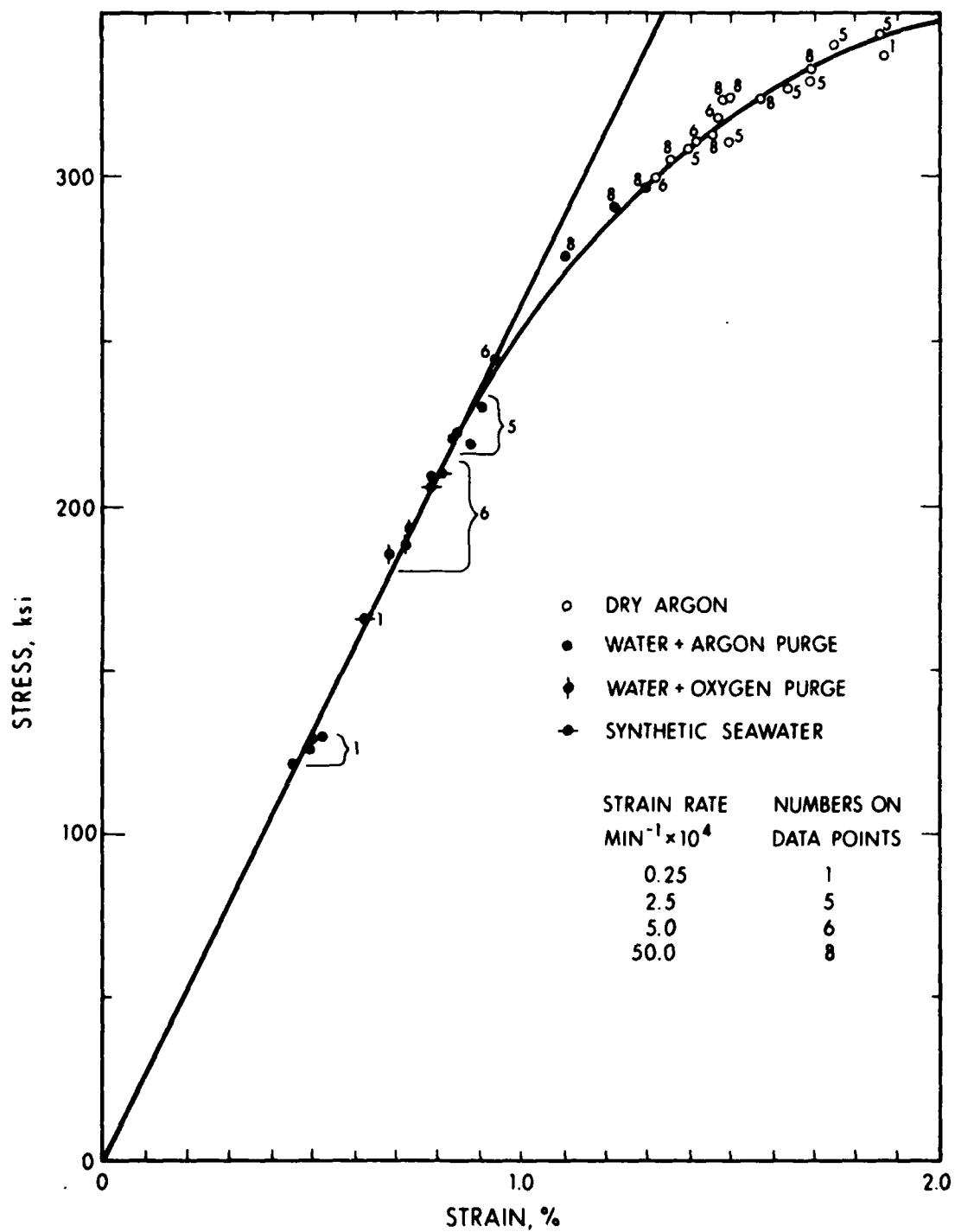


Figure 5
Stress and Strain at Fracture
Extensometric Method